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PAPR Reduction in ACO-OFDM Systems Based on BER Analysis

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ABSTRACT:

Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input and Multiple Output (MIMO) are two main techniques employed in 4th Generation Long Term Evolution (LTE). In OFDM multiple carriers are used and it provides higher level of spectral efficiency as compared to Frequency Division Multiplexing (FDM). In OFDM because of loss of orthogonality between the subcarriers there is intercarrier interference (ICI) and intersymbol interference (ISI) and to overcome this problem use of cyclic prefixing (CP) is required, which uses 20% of available bandwidth. Wavelet based OFDM provides good orthogonality and with its use Bit Error Rate (BER) is improved. Wavelet based system does not require cyclic prefix, so spectrum efficiency is increased. It is proposed to use wavelet based OFDM at the place of Discrete Fourier Transform (DFT) based OFDM in LTE. We have compared the BER performance of wavelets and DFT based OFDM.

Keywords: LTE; OFDM; DFT; Wavelet; BER.

I. INTRODUCTION:

As a multicarrier modulation technique, orthogonal frequency division multiplexing (OFDM) has been used in optical communication due to its high Spectral efficiency and resistance to inter-symbol Interference (ISI) [1]–[3]. Among the OFDM systems, intensity-modulated/direct-detection (IM/DD) OFDM system has been widely investigated in the cost-sensitive, short-range, and high-speed optical communications, such as indoor optical wireless communication, discrete multi-tone (DMT) systems and passive optical networks (PONs) [4]–[6].

As a popular IM/DD system, asymmetrically clipping optical OFDM (ACO-OFDM) has been extensively researched [8]–[10]. ACO-OFDM has a good power efficiency and the same optimal design for all constellation sizes due to the nonuse of DC bias, which is attractive to IM/DD sys-tem [8]. Recently, ACO-OFDM based on discrete Hartley transform (DHT) has been proposed for IM/DD system [11], [12]. DHT is a real trigonometric transform. Different from DFT-based ACO-OFDM, DHT-based ACO-OFDM does not need Hermit Ian symmetry (HS), and the same algorithm can be applied to the multiplexing and de multiplexing processes. When DFT and DHT have the same size, 2-pulse-amplitude modulation (2-PAM) (M-PAM)-modulated DHT-based ACO-OFDM transmits the same number of bits and has the same bit-error ratio (BER) performance as QPSK (M^2-QAM)-modulated DFT-based ACO-OFDM [11]–[13].

High peak-to-average power ratio (PAPR) is one of the major drawbacks of OFDM, which brings serious nonlinear distortion in both electronic and optical domain. Compared to OFDM without clipping operation, ACO-OFDM has a higher PAPR due to the same peak power but lower average power caused by clipping operation. Therefore, it is much more essential for ACO-OFDM to decrease PAPR. Among the PAPR reduction techniques, DFT-spread technique without any signal distortion and coding overhead has been widely studied [14]–[17]. To the best of our knowledge, the spread technique has not been investigated in DHT-based ACO-OFDM system. In this paper, we propose a DHT-spread technique for PAPR reduction in DHT-based ACO-OFDM and analyze the performance of DHT-spread technique by both simulations and experiments.

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Different from DFT-spread technique, DHT-spread technique has the real output, making it more suitable for the DHT-based ACO-OFDM system. At the complementary cumulative distribution function (CCDF) of 10^{-3}, the PAPR values of our proposed scheme are about 9.7 dB and 6.2 dB lower than those of conventional DHT-based ACO-OFDM without DHT-spread technique for 2-PAM and 4-PAM, respectively. The transmission experiment over 100-km standard single mode fiber (SSMF) had been realized to verify the feasibility of the proposed scheme. When the overall link rate was about 10 Gb/s, the proposed scheme had an about 7-dB improvement of received sensitivity at forward error correction (FEC) limit compared to conventional scheme. The proposed scheme has better performance on equalization and nonlinear distortion mitigation than the conventional scheme.

I-A. A Brief History of Wireless Optical Communications

The use of optical emissions to transmit information has been used since antiquity. Homer, in the Iliad, discusses the use of optical signals to transmit a message regarding the Grecian siege of Troy in approximately 1200 BC. Fire beacons were lit between mountain tops in order to transmit the message over great distances. Although the communication system is able to only ever transmit a single bit of information, this was by far the fastest means to transmit information of important events over long distances. In early 1790's, Claude Chappe invented the optical telegraph which was able to send messages over distances by changing the orientation of signaling "arms" on a large tower.

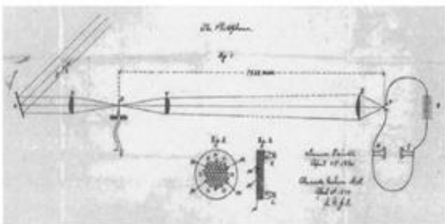

Fig. 1: Drawing of the photo phone by Alexander Graham Bell and Charles Sumner Tainter, April 1880 [The Alexander Graham Bell Family Papers, Library of Congress].

A code book of orientations of the signalling arms was developed to encode letters of the alphabet, numerals, common words and control signals. Messages could be sent over distances of hundreds of kilometers in a matter of minutes [8]. One of the earliest wireless optical communication devices using electronic detectors was the photo phone invented by A. G. Bell and C. S. Tainter and patented on December 14, 1880 (U.S. patent 235,496). Figure 1.2 presents a drawing made by the inventors outlining their system. The system is designed to transmit a operator's voice over a distance by modulating reflected light from the sun on a foil diaphragm. The receiver consisted of a selenium crystal which converted the optical signal into an electrical current. With this setup, they were able to transmit an audible signal a distance of 213 m [9].

The modern era of indoor wireless optical communications was initiated in 1979 by F.R. Gfeller and U. Bapst by suggesting the use of diffuse emissions in the infrared band for indoor communications [1]. Since that time, much work has been done in characterizing indoor channels, designing receiver and transmitter optics and electronics, developing novel channel topologies as well as in the area of communications system design. Throughout this book, previous work on a wide range of topics in wireless optical system will be surveyed. Communication systems transmit information from a transmitter to a receiver through the construction of a time-varying physical quantity or a signal .A familiar example of such a system is a wired electronic communications system in which information is conveyed from the transmitter by sending an electrical current or voltage signal through a conductor to a receiver circuit.

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Another example is wireless radio frequency (RF) communications in which a transmitter varies the amplitude, phase and frequency of an electromagnetic carrier which is detected by a receive antenna and electronics. In each of these communications systems, the transmitted signal is corrupted by deterministic and random distortions due to the environment. For example, wired electrical communication systems are often corrupted by random thermal as well as shot noise and are often frequency selective. These distortions due to external factors are together referred to as the response of a communications channel between the transmitter and receiver. For the purposes of system design, the communications channel is often represented by a mathematical model which is realistic to the physical channel. The goal of communication system design is to develop signaling techniques which are able to transmit data reliably and at high rates over these distorting channels.

In order to proceed with the design of signaling for wireless optical channels a basic knowledge of the channel characteristics is required. This chapter presents a high-level overview of the characteristics and constraints of wireless optical links. Eye and skin safety requirements as well as amplitude constraints of wireless optical channels are discussed. These constraints are fundamental to wireless optical intensity channels and do not permit the direct application of conventional RF signaling techniques. The propagation characteristics of optical radiation in indoor environments is also presented and contrasted to RF channels. The choice and operation of typical optoelectronics used in wire- less optical links is also briefly surveyed. Various noise sources present in the wireless optical link are also discussed to determine which are dominant. The chapter concludes with a comparison of popular channel topologies and a summary of the typical parameters of a practical short-range wireless optical channel.

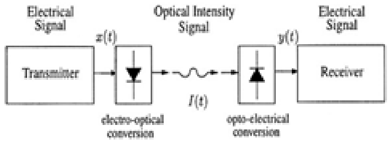

Fig.2: Block diagrm of wirless communication

I-B. WIRELESS OPTICAL INTENSITY CHANNELS

Wireless optical channels differ in several key ways from conventional communications channels treated extensively in literature. This section describes the physical basis for the various amplitude and power constraints as well as propagation characteristics in indoor environments**.**

BASIC CHANNEL STRUCTURE:

Most present-day optical channels are termed intensity modulated, direct detection channels. Figure 2.1 presents a schematic of a simplified free-space intensity modulated, direct-detection optical link. The optical intensity of a source is defined as the optical power emitted per solid angle in units of Watts persteradian [10]. Wireless optical links transmit information by modulating the instantaneous optical intensity, in response to an input electrical current signal The information sent on this channel is not contained in the amplitude, phase or frequency of the transmitted optical waveform, but rather in the intensity of the transmitted signal. Present day optoelectronics cannot operate directly on the frequency or phase of the range optical signal. This electro-optical conversion process is termed optical intensity modulation and is usually accomplished by a light-emitting diode (LED) or laser diode (LD) operating in the 850-950 nm wavelength band [11]. The electrical characteristics of the light emitter can be modeled as a diode, as shown in the figure. Section 2.2.1 describes the operation of LEDs and LDs in greater detail. The opt electrical conversion is typically performed by a silicon photodiode.

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The photodiode detector is said to perform direct-detection of the incident optical intensity signal since it produces an output electrical photocurrent, 2.1 Wireless Optical Intensity Channels 2.1.1 Basic Channel Structure Wireless Optical Intensity Channels 11 nearly proportional to the received irradiance at the photodiode, in units of Watts per unit area [10]. Electrically, the detector is a reversed biased diode, as illustrated in Figure 2.1. Thus, the photodiode detector produces an output electrical current which is a measure of the optical power impinging on the device. The photodiode detector is often termed a square law device since the device can also be modeled as squaring the amplitude of the incoming electromagnetic signal and integrating over time to find the intensity. Section 2.2.2 describes the operation of p-i-n and avalanche type photodiodes and discusses their application to wireless optical channels.

The underlying structure of the channel, which allows for the modulation and detection of optical intensities only, places constraints on the class of signals which may be transmitted. The information bearing intensity signal which is transmitted must remain non-negative for all time since the transmitted power can physically never be negative, i.e., Thus, the physics of the link imposes the fundamental constraint on signalling design that the transmitted signals remain non-negative for all time. In Chapters 4–6 this non-negativity constraint is taken into account explicitly in developing a framework for the design and analysis of modulation for optical intensity channels.

I-C. CHANNEL PROPAGATION PROPERTIES:

As is the case in radiofrequency transmission systems, multipath propagation effects are important for wireless optical networks. The power launched from the transmitter may take many reflected and refracted paths before arriving at the receiver. In radio systems, the sum of the transmitted signal and its images at the receive antenna cause spectral nulls in the transmission characteristic. These nulls are located at frequencies where the phase shift between the paths causes destructive interference at the receiver. This effect is known as multi path fading [19]. Unlike radio systems, multipath fading is not a major impairment in wireless optical transmission. The “antenna” in a wireless optical system is the light detector which typically has an active radiation collection area of approximately The relative size of this antenna with respect to the wavelength of the infrared light is immense, on the order of The multipath propagation of light produces fades in the amplitude of the received electromagnetic signal at spacing’s on the order of half a wavelength apart. As mentioned earlier, the light detector is a square law device which integrates the square of the amplitude of the electromagnetic radiation impinging on it. The large size of the detector with respect to the wavelength of the light provides a degree of inherent spatial diversity in the receiver which mitigates the impact of multipath fading [2].

Although multipath fading is not a major impediment to wireless optical links, temporal dispersion of the received signal due to multipath propagation remains a problem. This dispersion is often modeled as a linear time invariant system since the channel properties change slowly over many symbol periods [1, 20]. The impact of multipath dispersion is most noticeable in diffuse infrared communication systems In short distance line-of-sight (LOS) links, multipath dispersion is seldom an issue. Indeed, channel models proposed for LOS links assume the LOS path dominates and model the channel as a linear attenuation and delay [21]. The modeling of the multipath response in a variety of indoor environments has been carried out to allow for computer simulation of communication systems. Gfeller and Bapst [1] introduced the concept of using diffuse optical radiation for indoor communication as well as defining the first simulation model.

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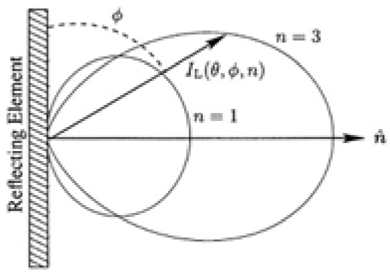

Fig.3: Lambertian intensity pattern

In their model, each surface in an indoor environment is partitioned into a set of reflecting elements which scatter incident optical radiation. A key assumption is that, regardless of the angle of incidence, each element scatters light with a Lambertian intensity pattern,

$$I_L(\theta,\phi,n) = P_{\text{total}}\frac{n+1}{2\pi}\cos^n\phi \qquad [\text{W/sr}]$$

where is the total reflected power, is the mode number of the radiation pattern and angles and are the polar and azimuthal angles respectively with respect to a normal, to the reflecting element surface. The Lambertian optical intensity distribution is normalized so that integrating it over a hemisphere gives The mode number is a measure of the directivity of the reflected diffuse intensity distribution and typical values for plaster walls are near unity [1]. Figure 2.2 presents a plot of a cross-section of the Lambertian radiation pattern for Notice that this Lambertian radiation pattern models only diffuse reflections from surfaces and not specular reflections.In the Gfeller and Bapst model, the received power is simply the power from every element. There has been a continued interest in defining mathematical and simulation models for the multipath response of a variety of indoor settings. New, more accurate, analytic and simulation models have been developed which take into account multiple reflections as well as allow for fast execution time [22, 23, 21, 24, 25]. Additionally, experimental investigations have also been done to measure the response of a large number of channels and characterize the delay spread, path loss as well as investigating the impact of rotation [26, 20, 27].

Typical bandwidths for the multipath distortion is on the order of 10-50MHz[11].

Optoelectronic Components

The basic channel characteristics can be investigated more fully by considering the operation of the optoelectronic devices alone. Device physics provides significant insight into the operation of these optoelectronic devices. This section presents an overview of the basic device physics governing the operation of certain optoelectronic devices, emphasizing their benefits and disadvantages for wireless optical applications.

Light Emitting Devices

Solid state light emitting devices are essentially diodes operating in forward bias which output an optical intensity approximately linearly related to the drive current. This output optical intensity is due to the fact that a large proportion of the injected minority carriers recombine giving up their energy as emitted photons. To ensure a high probability of recombination events causing photon emission, light emitting devices are constructed of materials known as direct band gap semiconductors. In this type of crystal, the extrema of the conduction and valence bands coincide at the same value of wave vector. As a result, recombination events can take place across the band gap while conserving momentum, represented by the wave vector (as seen in Figure 2.3)[28]. A majority of photons emitted by this process have energy where is the band gap energy, is Planck's constant and is the photon frequency in hertz. This equation can be re-written in terms of the wavelength of the emitted photon as

$$\lambda = \frac{1240}{E_g}$$

where is the wavelength of the photon in nm and is the band gap of the material in electron-Volts. Commercial direct band gap materials are typically compound semiconductors of group III and group V elements. Examples of these types of crystals include: GaAs, InP, InGaAsP and AlGaAs (for Al content less

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than 0.45) [29]. Elemental semiconducting crystals silicon and germanium are indirect band gap materials. In these types of materials, the extreme a of conduction and valence bands do not coincide at the same value of wave vector as shown in Figure 2.3. Recombination events cannot occur without a variation in the momentum of the interacting particles. The required change in momentum is supplied by collisions with the lattice. The lattice interaction is modeled as the transfer of phonon particles which represent the quantization of the crystalline lattice vibrations. Recombination is also possible due to lattice defects or due to impurities in the lattice which produce energy states within the band gap [29, 31]. Due to the need for a change in momentum for carriers to cross the band gap, recombination events in indirect band gap materials are less likely to occur. Furthermore, when recombination does take place, most of the energy of recombination process is lost to the lattice as heat and little is left for photon generation. As a result, indirect band gap materials produce highly inefficient light emitting devices [30].

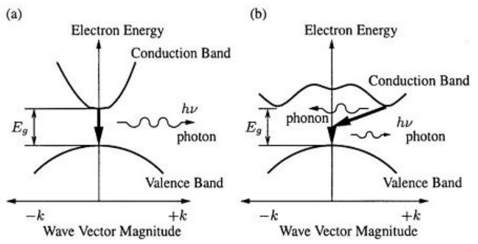

Figure 2.3. An example of a one dimensional variation of band edges with wave number (k) for (a) direct band gap material, (b) indirect band gap material (based on [30]).

II.DEVELOPMENT OF OFDM SYSTEMS

The development of OFDM systems can be divided into three categories. This comprises of

1. Frequency Division Multiplexing
2. Multicarrier Communication
3. Orthogonal Frequency Division Multiplexing.

1. Frequency Division Multiplexing

Frequency Division Multiplexing (FDM) is a networking technique in which multiple data signals are combined for simultaneous transmission via a shared communication medium. Frequency Division Multiplexing is a form of signal multiplexing which involves assigning non – overlapping frequency ranges or channels to different signals or to each ''user'' of a medium. A gap or guard band is placed between each channel to ensure that the signal of one channel does not overlap with the adjacent channel. FDM is used to allow multiple users to share a single physical communications medium (i.e. not broadcast through the air), the technology is called frequency-division multiple access (FDMA). Due to lack of digital filters it was difficult to filter closely packed adjacent channels.

2. Multicarrier Communication

Multicarrier communication is incompetent to transfer a high rate data stream through a channel. The data stream signal is split into number of signals over that frequency range. Each of these signals are separately modulated by a separate carrier signals. Each of these modulated signals is transmitted over a channel. The individual carriers have narrow bandwidth, but the composite signal can have broad bandwidth. At the receiver end, this individual modulated signal is fed to a de multiplexer, where all the signals are combined and form a original signal with a broad bandwidth. Its advantages are immunity to delay spread and efficient bandwidth usage. Limitations include it acquires high PAPR.

3. Orthogonal Frequency Division Multiplexing (OFDM)

The nature of future wireless applications demands high data rates. Naturally dealing with ever-unpredictable wireless channel at high data rate communications is not an easy task. With the ever growing demand of wireless communication in this generation various modulation techniques are introduced. Orthogonal frequency-division multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. OFDM is a special form of multi-carrier transmission where all the subcarriers are orthogonal to each other.

OFDM is a frequency division multiplexing (FDM) scheme utilized as a digital multi carrier modulation method. In OFDM a large number of closely spaced orthogonal sub carriers is used to carry data. The data is divided into several parallel streams for each sub carriers. By maintaining total data rates similar to the conventional single carrier modulation schemes in the same bandwidth. At a low symbol rate each subcarrier is modulated with a conventional modulation scheme (such as QPSK). OFDM promises a high user data rate transmission capability at a reasonable complexity and precision. OFDM has developed into a popular scheme for wideband digital communication, used in applications such as digital television and audio broadcasting, DSL Internet access, wireless networks, power line networks, and 4G mobile communications.

OFDM theory

Orthogonal Frequency Division Multiplexing is a special form of multicarrier modulation. . An OFDM signal consists of a number of closely spaced modulated carriers. In OFDM, carriers are orthogonal and independent to each other. When modulation of any form - voice, data, etc. is applied to a carrier, then sidebands spread out either side. As well as in OFDM the signals are transmitted close to one another as shown in below figure. It is necessary for a receiver to be able to receive the whole signal and successfully demodulate the data. For transmitting the close signals, a filter with a guard band is used at the receiver side to separate the signals and transmit. Although the sidebands from each carrier overlap, they can still be received without the interference that might be expected because they are orthogonal to each another. This is achieved by having the carrier spacing equal to the reciprocal of the symbol period.

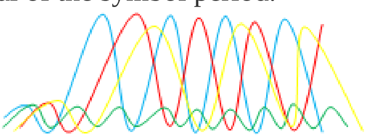

Fig. 4: Orthogonally in orthogonal frequency division multiplexing (OFDM)

Orthogonally

Two periodic signals are orthogonal when the integral of their product over one period is equal to zero.
For the case of continuous time:

$$\int_{0}^{T} \cos(2\pi n f_0 t)\cos(2\pi m f_0 t) = 0,$$

For the case of discrete time:

$$\sum_{k=0}^{N-1} \cos\left(\frac{2\pi kn}{N}\right)\cos\left(\frac{2\pi km}{N}\right) dt = 0$$

Where m ≠ n in both cases.

Sub – Carriers

Each sub – carrier in an OFDM system is a sinusoid with a frequency that is an integer multiple of a fundamental frequency. Each sub – carrier is like a Fourier series component of the composite signal, an OFDM symbol. The sub – carrier's waveform can be expressed as

$$s(t) = \cos(2\pi f_c t + \theta_k)$$

$$`= a_n \cos(2\pi n f_0 t) + b_n \sin(2\pi n f_0 t)$$

$$= \sqrt{a_n^2 + b_n^2} \cos(2\pi n f_0 t + \varphi_n)$$

Where $\varphi_n = \tan^{-1}\left(\frac{b_n}{a_n}\right)$

The sum of the sub – carriers is then the baseband OFDM signal:

$$s_B(t) = \sum_{n=0}^{N-1} \{a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t)\}$$

Inter – Symbol Interference

Inter symbol interference is a signal distortion in telecommunication. One or more symbols can interfere with other symbols causing noise or a less reliable signal. The main causes of inter symbol interference are multipath propagation or non-linear frequency in channels. This has the effect of a blur or mixture of symbols, which can reduce signal clarity. Due to the presence of ISI in the system error is introduced at the receiver.

If inter symbol interference occurs within a system, the receiver output becomes erroneous at the decision device. This is an unfavorable result that should be reduced to the most minimal amount possible. Error rates from inter symbol interference are minimized through the use of adaptive equalization techniques and error correcting codes.

Inter – Carrier Interference

Inter carrier Interference (ICI) is well known to degrade performance of Orthogonal Frequency Division Multiplexing (OFDM) transmissions. It arises from carrier frequency offsets (CFOs), from the Doppler spread due to channel time-variation and, to a lesser extent, from sampling frequency offsets (SFOs). Interference is observed between sub carriers of the resultant signal. This is known as inter – carrier interference (ICI).

CYCLIC PREFIX

The cyclic prefix acts as a buffer region or guard interval to protect the OFDM signals from inter symbol interference. This can be an issue in some circumstances even with the much lower data rates that are transmitted in the multicarrier OFDM signal. Cyclic prefix is added to the front of the symbol in the transmitted stream, and is removed before modulation at the receiver.

Synchronization

Synchronization is an important step that must be performed at the receiver in OFDM systems, before an OFDM receiver starts demodulating subcarriers. Synchronization of an OFDM signal requires finding the symbol timing and carrier frequency offset. Symbol timing for an OFDM is significantly different than for a single carrier signal, since there is not an “eye opening” where a best sampling time can be found. Rather there are hundreds of samples per OFDM symbol as number of samples is directly proportional to number of subcarriers. There is some tolerance for symbol timing errors when a cyclic prefix is used to extend the symbol.

But synchronization of carrier frequency at the receiver must be done accurately, failing which, there will be loss of orthogonally between subcarriers resulting in performance degradation. There are several advantages and disadvantages attached to the use for the cyclic prefix within OFDM.

Advantages

- Provides robustness: The addition of the cyclic prefix adds robustness to the OFDM signal. The data that is retransmitted can be used if required.
- Reduces inter-symbol interference: The guard interval introduced by the cyclic prefix enables the effects of inter-symbol interference to be reduced.

Disadvantages

- Reduces data capacity: As the cyclic prefix re-transmits data that is already being transmitted, it takes up system capacity and reduces the overall data rate.
- Sensitive to Doppler effect

OFDM BASED MULTIPLE ACCESS

Various multiple access schemes can be combined with OFDM transmission and they include orthogonal frequency division multiplexing-time division multiple access (OFDM-TDMA), OFDMA, and multicarrier code division multiple access (MCCDMA). In OFDM-TDMA, time-slots in multiples of OFDM symbols are used to separate the transmissions of multiple users. This means that all the used subcarriers are allocated to one of the users for a finite number of OFDM symbol periods. The only difference from OFDM-TDMA is that the users capture the channel and use it for certain duration, i.e., the time dimension is used to separate the user signals. In OFDMA systems, both time and/or frequency resources are used to separate the multiple user signals. Groups of OFDM symbols and/or groups of subcarriers are the units used to separate the transmissions to/from multiple users.

The time, frequency view of a typical OFDMA signal is shown in a case where there are 3 users. Users" signals are separated either in the time-domain by using different OFDM symbols and/or in the subcarrier domain. Thus, both the time and frequency resources are used to support multiuser transmissions.

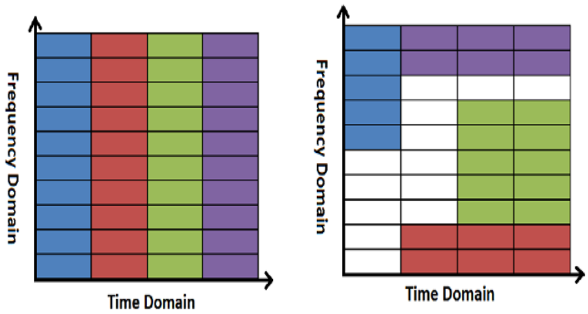

Fig.5: Difference between OFDM and OFDMA resource by user allocation.

The OFDM technique divides the total bandwidth into many narrow sub-channels and sends data in parallel. It has various advantages, such as high spectral efficiency, immunity to impulse interference and, frequency selective fading without having powerful channel equalizer. But one of the major drawbacks of the OFDM system is high PAPR. OFDM signal consists of lot of independent modulated subcarriers, which are created the problem of PAPR. It is impossible to send this high peak amplitude signals to the transmitter without reducing peaks. So we have to reduce high peak amplitude of the signals before transmitting.

V. PROPOSED METHOD

The block diagram of a (CLIP/CLAMP) Flip-OFDM transmitter with N subcarriers is illustrated in Fig. 6 [9]. To ensure that the time-domain signal is real in IM/DD systems, the input data vector X = [X(0), X(1), · · · , X(N − 1)]T should satisfy the Hermitian symmetry property, i.e.,

$$X(k) = X^*(N-k),\ k = 1, 2, \cdots, N/2-1. \qquad (1)$$

Note that X(0) and X(N=2) are usually set to zero since the DC part of OFDM signal is left unused in practical applications.

Hence, the time-domain signal vector x = [x(0),x(1),…., x(N-1)] after inverse fast Fourier transform (IFFT) operation can be represented as

$$\begin{aligned} x(n) &= \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) \exp(j2\pi kn/N) \\ &= \frac{2}{\sqrt{N}} \sum_{k=1}^{N/2-1} \mathrm{Re}\left[X(k) \exp(j2\pi kn/N)\right] \qquad (2) \\ & n = 0, 1, \cdots, N-1. \end{aligned}$$

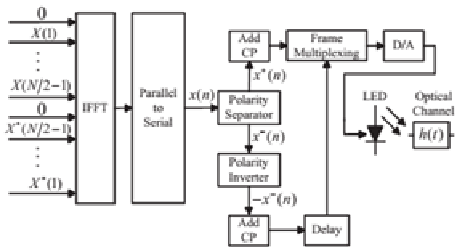

Fig. 6. Block diagram of a Flip-OFDM transmitter.

PRINCIPLE:

The multiplexing/de multiplexing processes of the proposed OFDM scheme use the DHT algorithm. DHT is a real trigonometric trans-form with a self-inverse property. Unlike the DFT-based IM/DD OFDM, DHT-based IM/DD OFDM does not need HS to generate real signal and the multiplexing and de multiplexing processes employ the same algorithm. Next, if no otherwise specified, all the multiplexing/de multiplexing processes of OFDM mentioned below use the DHT algorithm. The block diagram of DHT-spread ACO-OFDM (DHT-S-ACO-OFDM) for IM/DD system is depicted in Fig. 1. Unlike conventional ACO-OFDM, DHT-S-ACO-OFDM adds two L-point DHT modules in the transmitter and receiver as the red boxes show. At transmitter, the data sequences are sent to the real constellation mapper [PAM mapper] after serial-to-parallel operation. Then the generated M-PAM signals are sent to the L-point DHT to realize the DHT-spread operation.

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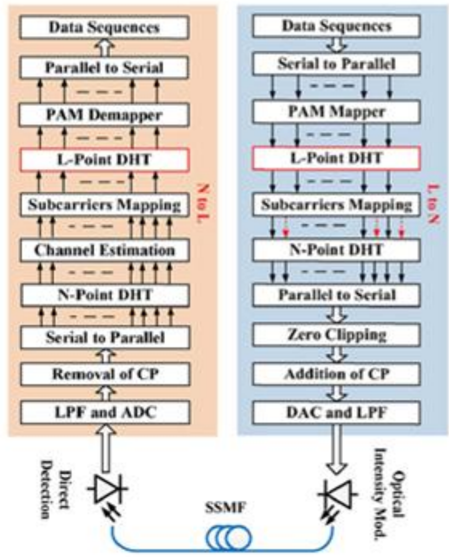

Fig. 7. Block diagram of DHT-spread ACO-OFDM for IM/DD system.

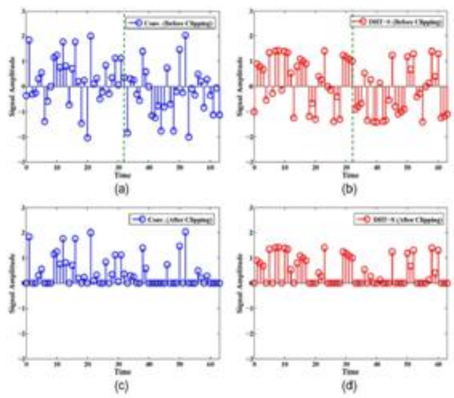

Fig. 8. (a) Anti-symmetry conventional OFDM symbol. (b) Anti-symmetry DHT-S-OFDM symbol. Conventional ACO-OFDM symbol. (d) DHT-S-ACO-OFDM symbol. The N is equal to 64.

TIME DOMAIN:

Fig. 8 shows time domain symbols before and after clipping operation in conventional ACO-OFDM and DHT-S-ACO-OFDM where N is set to 64. As shown in Fig. 2(a) and (b), the green dash line points out the position of the 32nd sample. Obviously, the symbols before clipping operation in conventional ACO-OFDM and DHT-S-ACO-OFDM systems are both anti-symmetry.

The average power of the symbol after clipping operation is half that of the symbol before clip-ping operation. PAPR of the symbols after clipping operation are theoretically 3 dB higher than that of the symbols before clipping operation. Consequently, it is much more essential for ACO-OFDM to decrease the PAPR. We have set the symbols in Fig. 2(c) and (d) with the same average power, the symbol in Fig. 2(c) obviously has larger peak power than the symbol in Fig. 2(d). PAPR of DHT-S-ACO-OFDM should be lower than that of conventional ACO-OFDM.

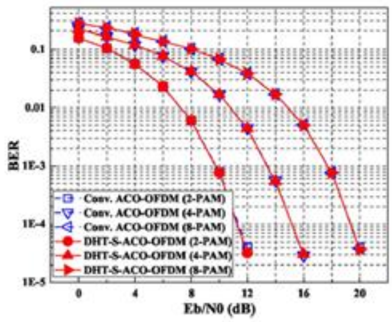

Fig. 9. Comparison of BER performance between conventional ACO-OFDM and DHT-S-ACO-OFDM in AWGN channel BER Performance in AWGN Channel

Fig. 9 depicts BER performance of conventional ACO-OFDM and DHT-S-ACO-OFDM where N is 256 in additive white Gaussian noise (AWGN) channel. When the same simulation parameters are adopted, BER curves of DHT-S-ACO-OFDM coincide to those of conventional ACO-OFDM. We can draw a conclusion that the BER performance of DHT-S-ACO-OFDM is the same as that of conventional ACO-OFDM. The BER performance

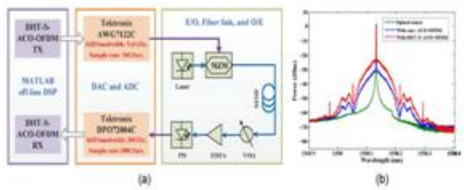

Fig. 10. (a) Experimental setup of DHT-S-ACO-OFDM. (b) Optical spectrum for DHT-S-ACO-OFDM and conventional ACO-OFDM.

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of DHT-S-ACO-OFDM is not influenced by DHT-spread operation in AWGN channel.

VI. EXPERIMENT SETUP AND RESULTS

VII. STANFORD UNIVERSITY INTERIM (SUI) CHANNEL MODELS

This is a set of 6 channel models representing three terrain types and a variety of Doppler spreads, delay spread and line-of-sight/non-line-of-site condition that are typical of the continental US as follows[Erceg2001]

TABLE 1: Terrain Type and Doppler Spread for SUI Channel Models

Channel	Terrain Type	Doppler Spread	Spread	LOS
SUI-1	C	Low	Low	High
SUI-2	C	Low	Low	High
SUI-3	B	Low	Low	Low
SUI-4	B	High	Moderate	Low
SUI-5	A	Low	High	Low
SUI-6	A	High	High	Low

CONCLUSION:

In this letter, we studied how nonlinear distortion due to PDHPA affects BER degradation for transmitted downlink DSCDMA signals. We established analytically how the threshold exceeding rate RE and the variance of the clipped portion of the signal σ2c contribute to BER degradation. The motivation of this work is to provide system designers/operators with efficient tools that provide potential insight into the interactions between CDMA signals and the nonlinear PD-HPA, leading to better understanding of the impact of the PD-HPA on system BER. Moreover, establishing these characteristics for the input signal in relation to the PD-HPA characteristics opens new avenues for research to minimize the effect of nonlinear distortion before the signal even hits the amplifier.

For instance, in search and optimization techniques such as the selected mapping technique, where many representations of the same signal are generated and the one that achieves the minimum of these characteristics is selected for transmission.

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